



NGST Wavefront Control

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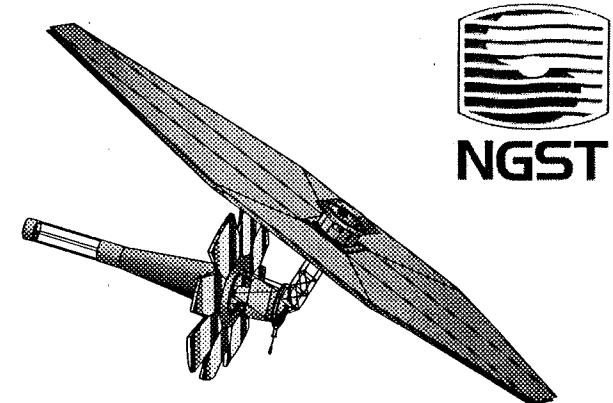
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March 29, 2000

NGST from a WFS&C Perspective



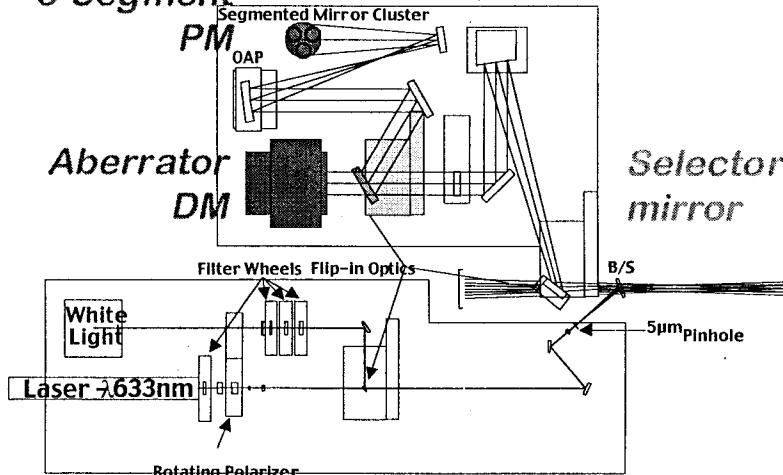
- Segmented primary mirror
- Segments and SM deployed to 5 mm piston, 5 mrad tilt accuracy
- Segments actuated in rigid-body DOFs
- Deformable segments or quartenary mirror provides means of correcting segment figure errors
- NIR and MIR cameras provide 1-16 mm imaging, can be used for WF sensing
- Very low temperature change across operating envelope
- Very low effective system CTE (may include active thermal control)
- Very low vibration and slew environment

Wavefront Control Testbed (WCT)

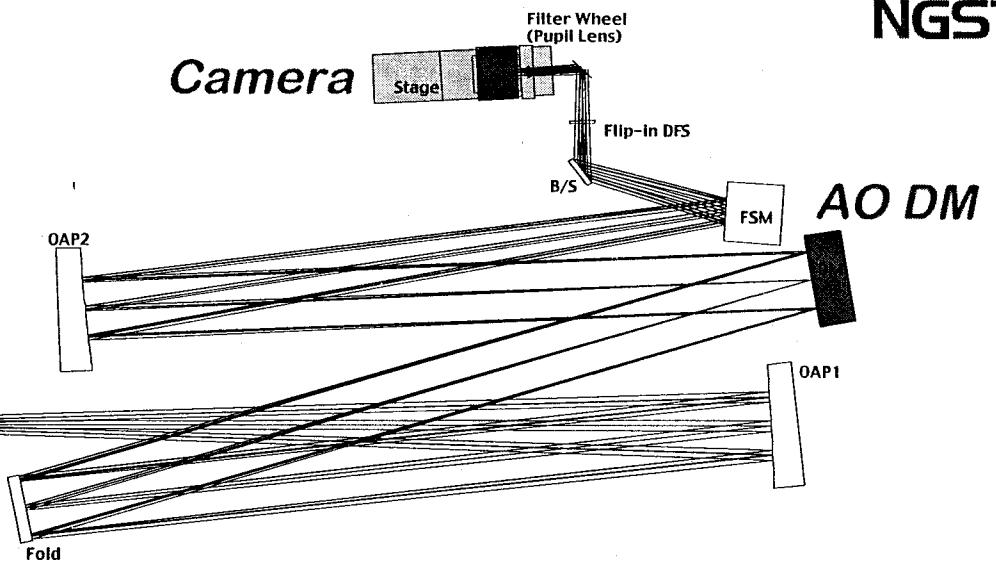


Telescope Simulator

3-Segment



Camera



Source Module

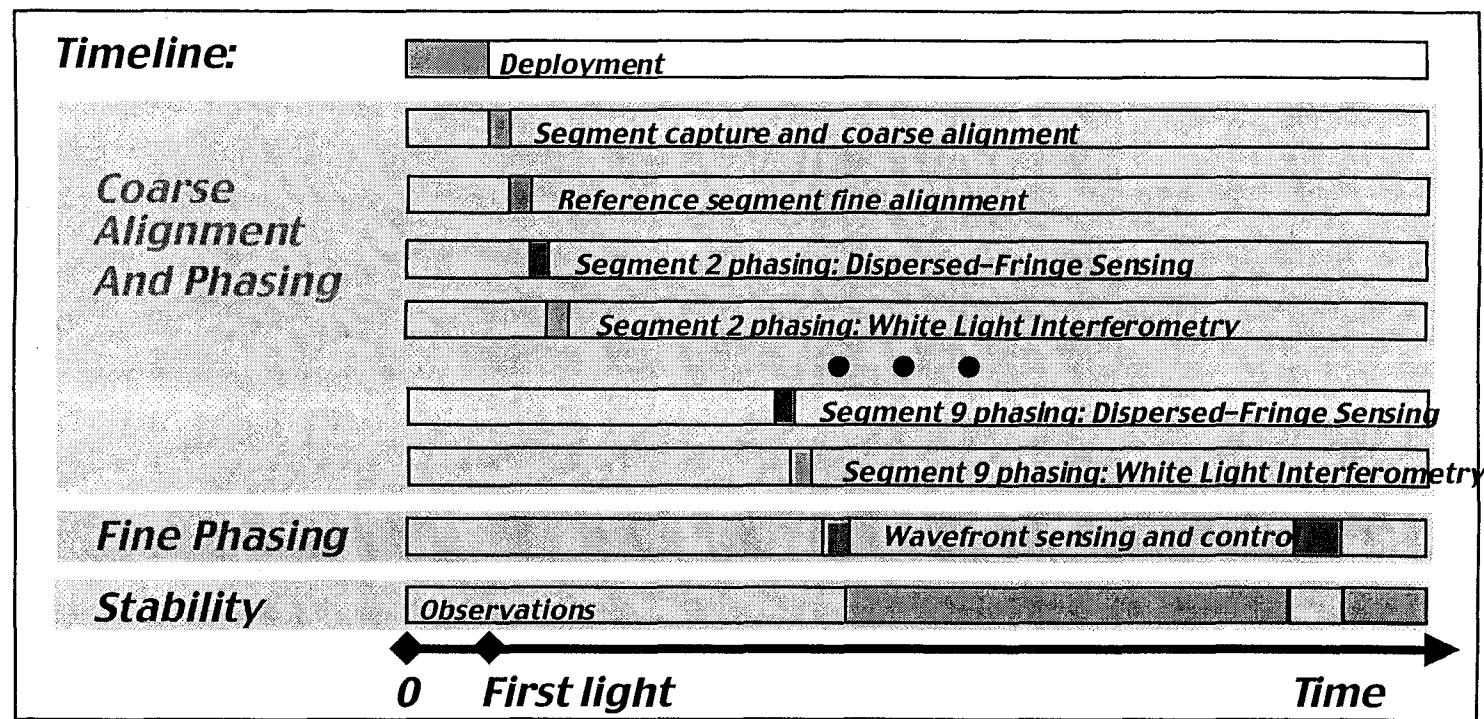
- Typical experiment uses Telescope Simulator (TSM) to inject errors
 - WCT-1: 97-actuator DM
 - WCT-2: 3 small segments
- Errors are sensed using WFS CCD camera
- Corrections implemented using AO DM and segments



NGST

NGST Baseline WFC

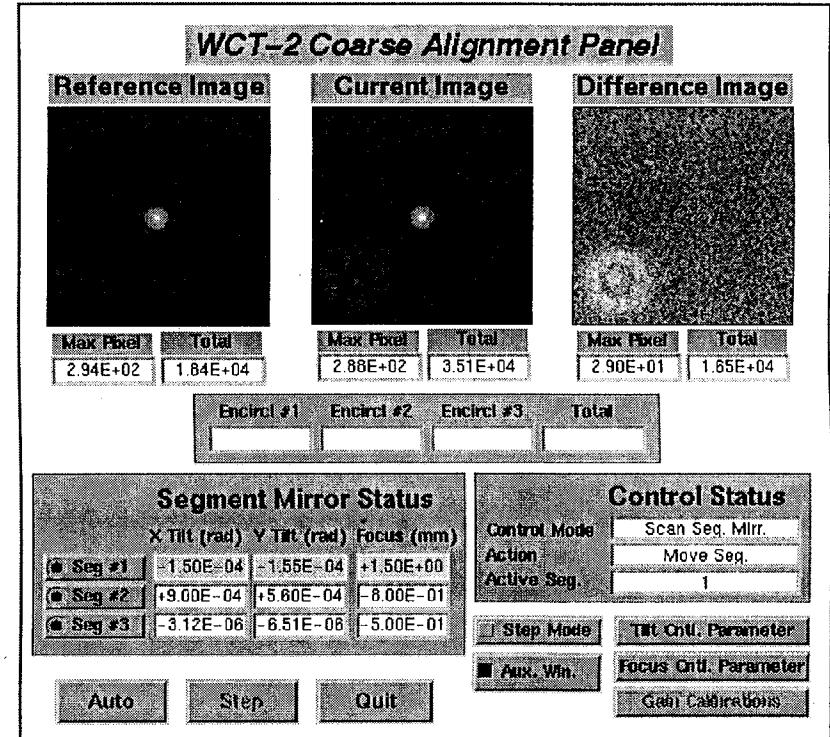
- WFC functions are performed using the science cameras
- Control is split into distinct phases:
 - Initial Capture, Coarse Align and Coarse Phasing control follows deployment
 - + WFE goes from mm to um
 - Fine Phasing follows initial phasing
 - + WFE goes from um to nm
 - Fine Phasing is repeated throughout the mission
 - + Dedicated observations or simultaneous with science observations, using other camera
- Figure is held passively during observation period





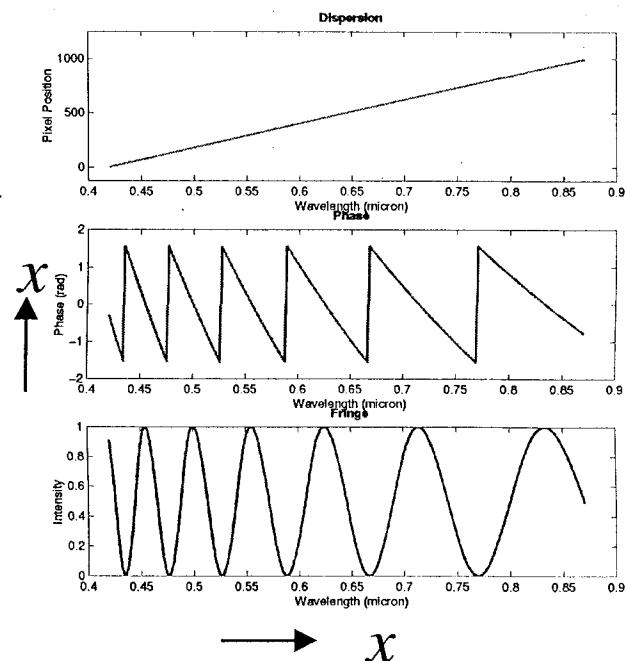
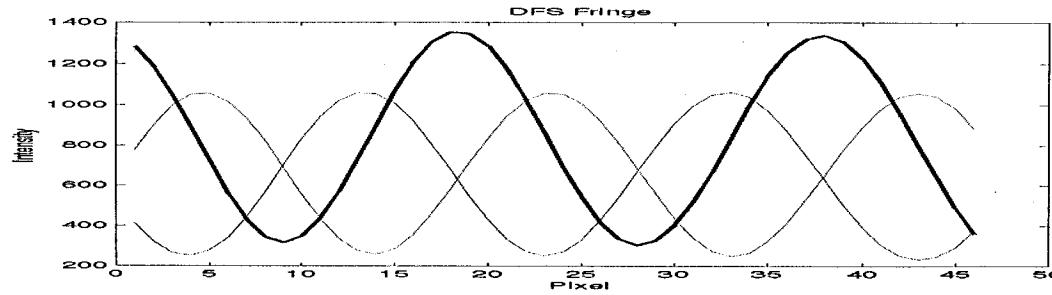
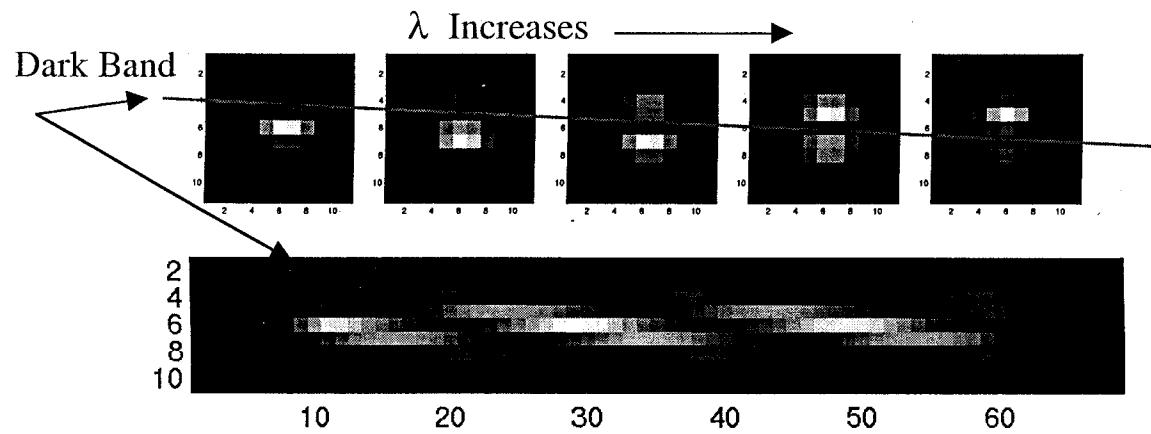
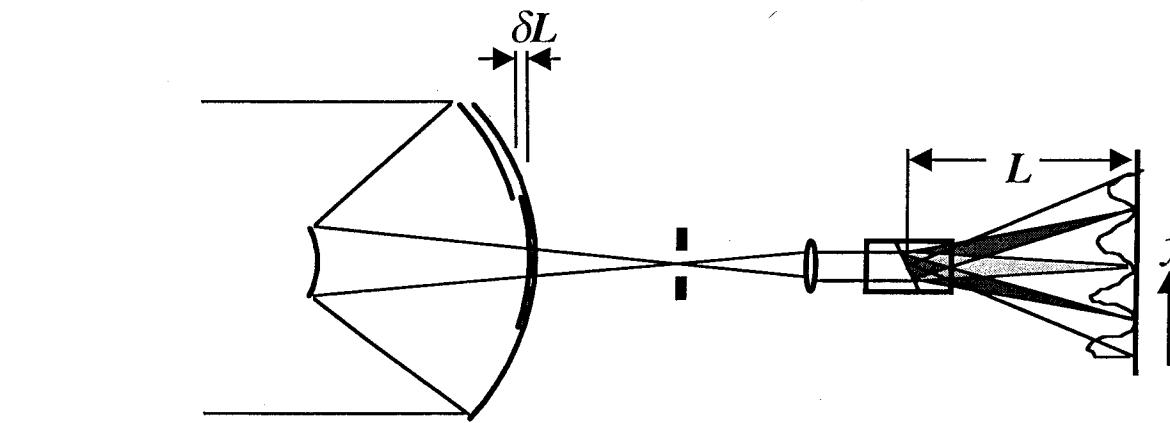
Capture and Coarse Alignment

- Performed at first light, while pointed at a bright, isolated star
- Segment is tilted slightly, frames differenced, and difference frame is thresholded
- If difference exceeds threshold, spot is centroided, and the spot is driven to the center of the field
- Otherwise, scan segment to next (4 amin) FOV and repeat.
- Focus each segment by maximizing 3-tier encircled energy metric



Companion paper by Shi et al...

Coarse Phasing: DFS Fringe Signals



- Spacing of fringes indicates piston magnitude
- Angle of fringes indicates piston sign

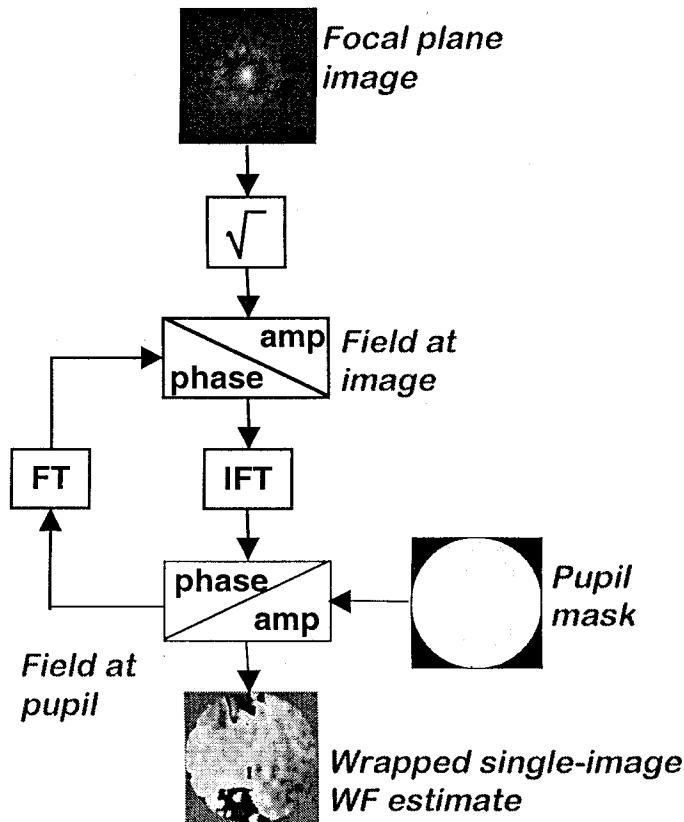
Companion paper by Shi et al...



Phase Retrieval for WF Sensing

- Excellent accuracy and high spatial resolution
- Works across segment discontinuities, modulo 2 pi
- Sensing at 2 or more wavelengths can resolve segment piston over a very large range
- Robust to noise and blurring effects
- Reasonable dynamic range when used with phase unwrapping
- Large dynamic range when both NIR and MIR cameras used
- Does not require a dedicated sensor
- Can measure the entire optical train in all science cameras
- Does not require extraneous or non-common path optics

Gerchberg-Saxton Iterative-Transform PR

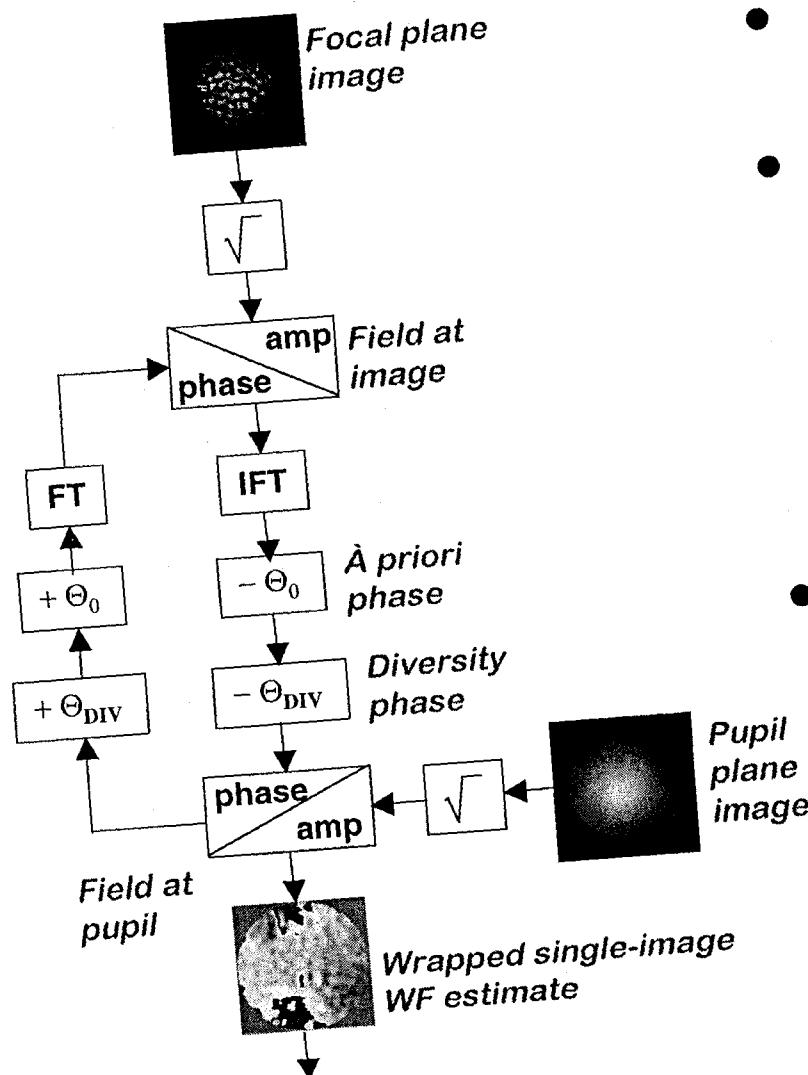


- Imaging system f/no., pixel size, aperture mask, λ all known
- Starts with a random guess at the phase in the exit pupil
- Iterates on pupil complex field until changes between iterates are small
- Pupil phase is angle of pupil field
- Produces high-resolution pupil map which matches image

But...

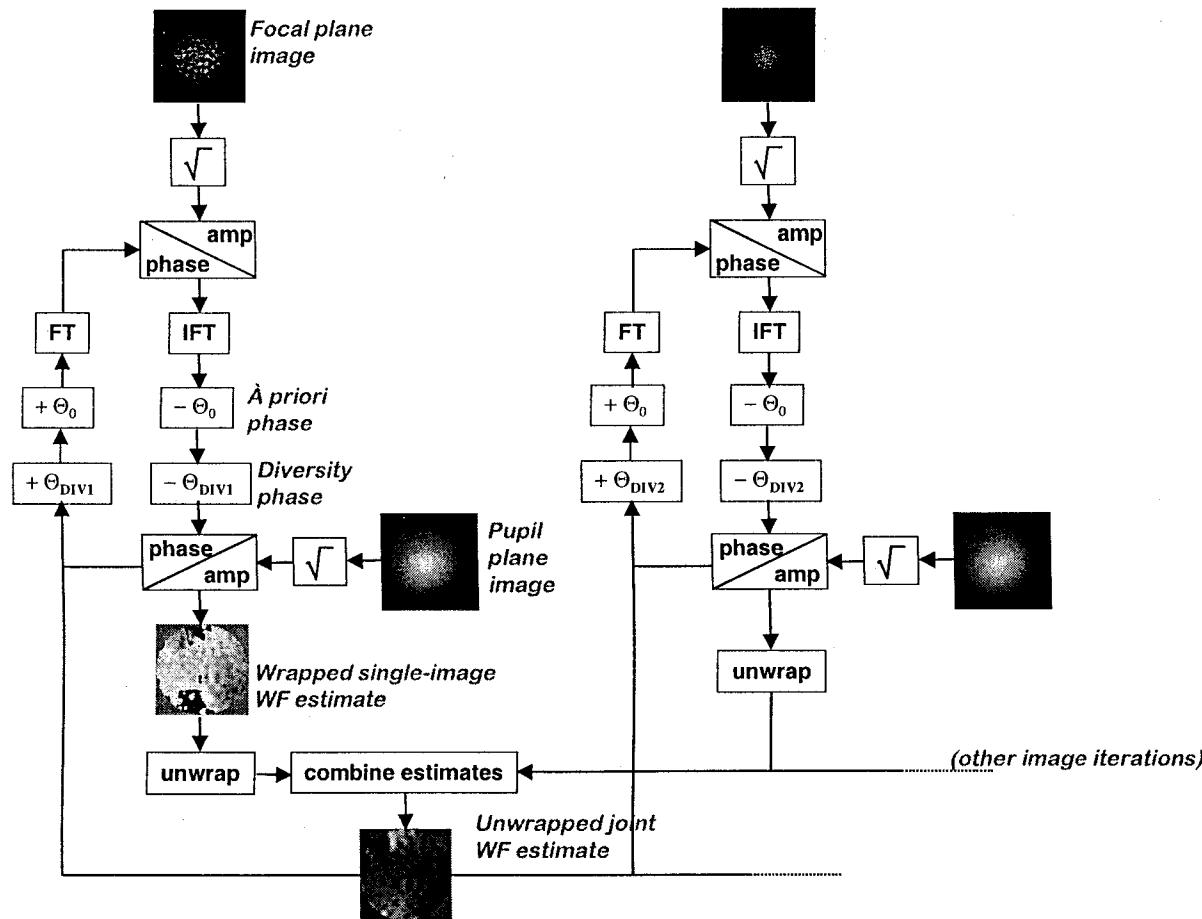
- Solution non-unique
- In-focus image susceptible to noise

Modified Gerchberg-Saxton Inner Loop



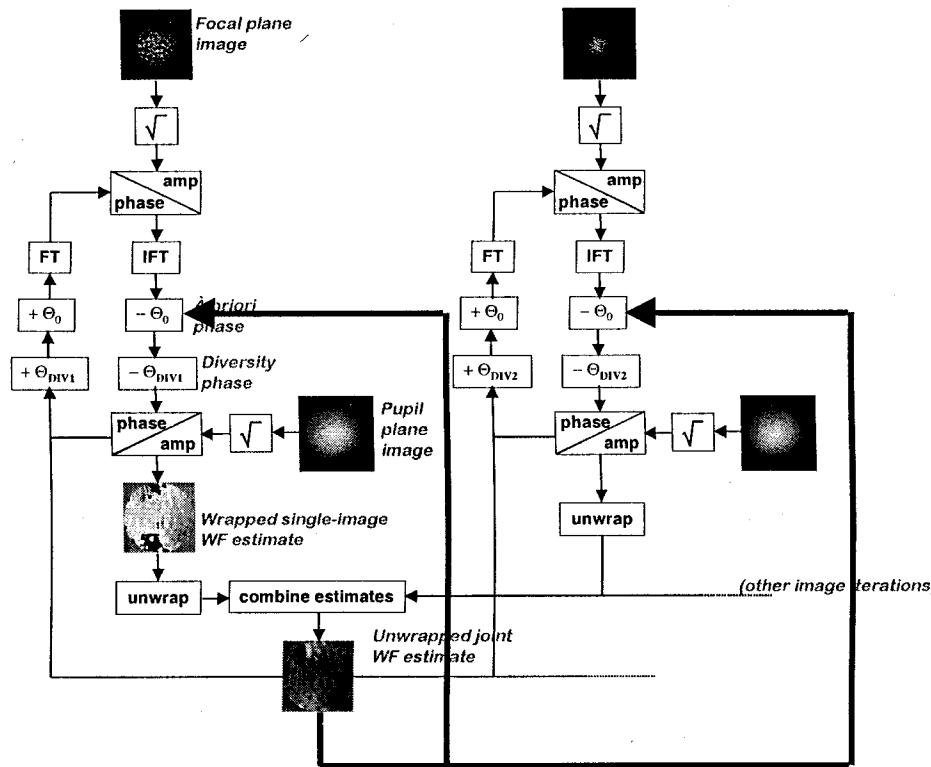
- Pupil image data replaces mask, halves number of unknowns
- Defocussed images improve visibility of aberrations
 - Spread out effects over many pixels
 - Reduce impact of jitter, other blurring
 - Reduce contrast between low, high-f effects
- Subtracting known phase (Θ_0, Θ_{DIV}) from the phase iteration reduces the iteration dynamic range
 - Θ_0 is systematic across all images
 - Θ_{DIV} is difference between images from embedded MACOS model

MGS Outer Loop (cont.)



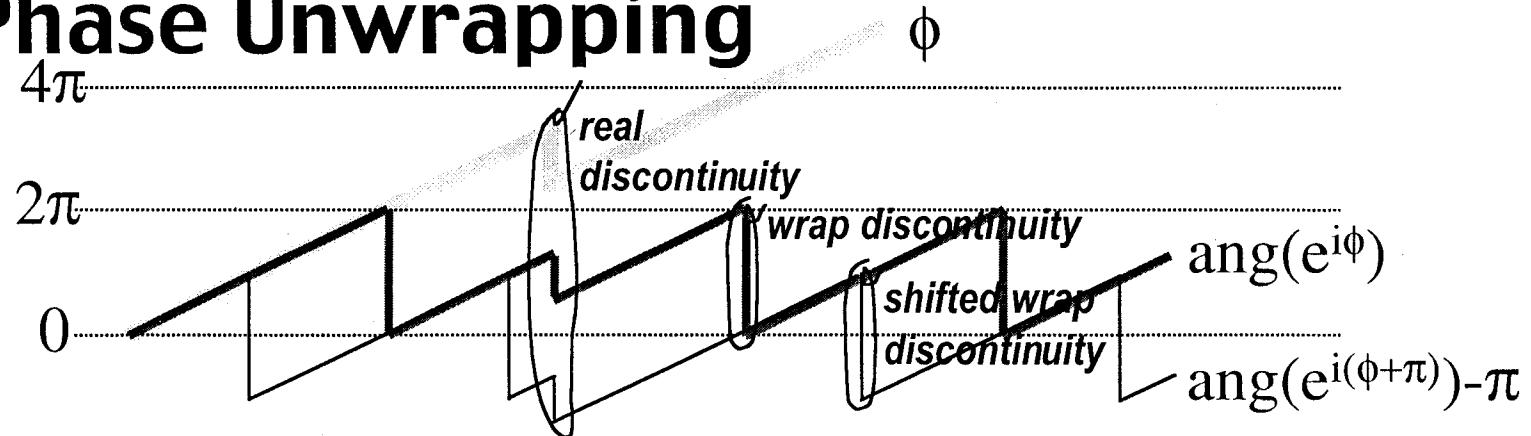
- Multiple images overdetermine solution to ensure uniqueness
 - Provides more data without introducing new unknowns
- Phase unwrapping allows estimation of $WFE > \lambda$
 - Joint unwrapping improves unwrapping robustness

MGS Outer Outer Loop



- Feedback of estimates reduces dynamic range of iterates

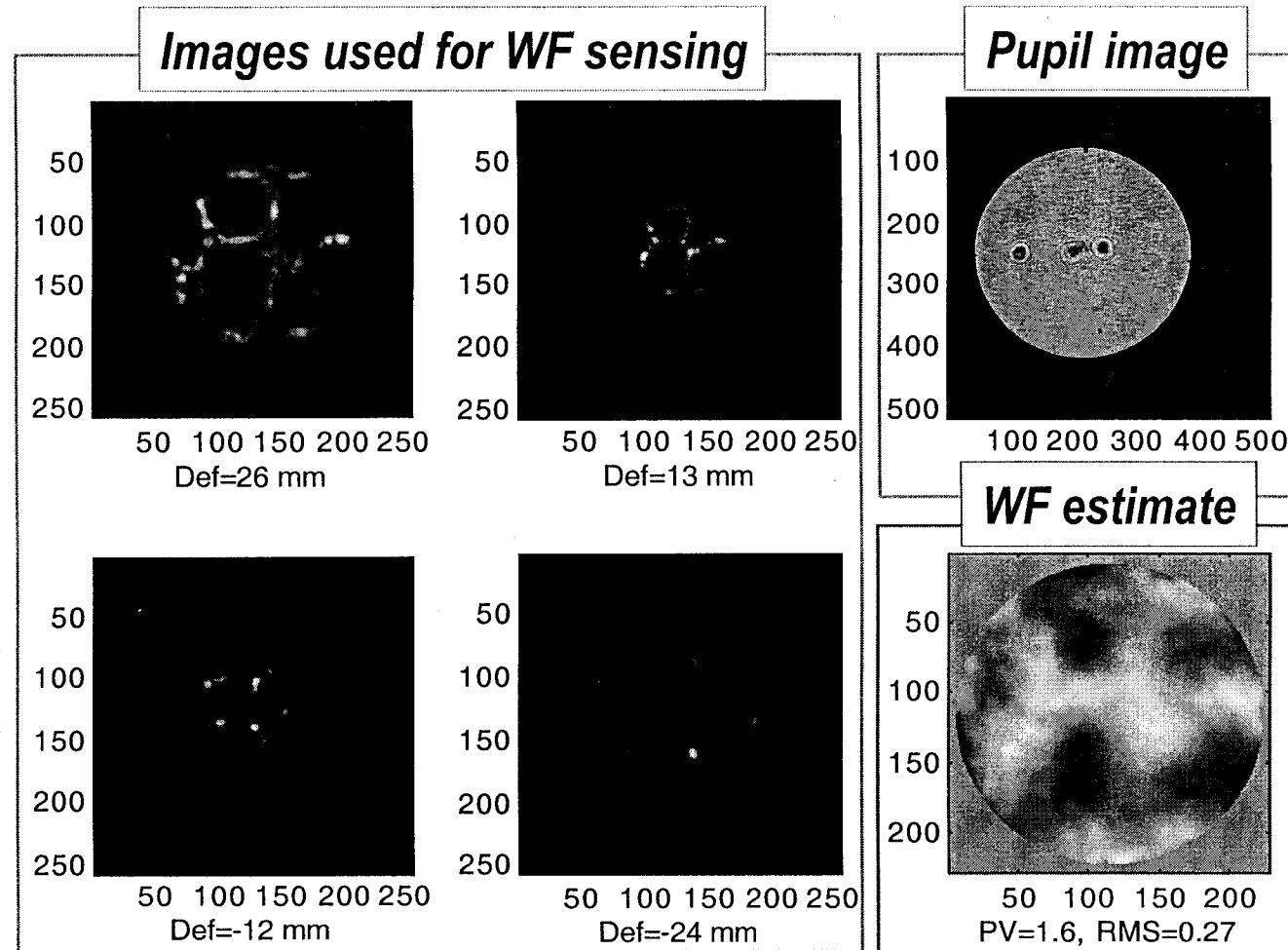
Phase Unwrapping



- Choice:
 1. A simple, fast, imperfect unwrapping algorithm
 2. A complex, slow, imperfect unwrapping algorithm
- We went with (1)
 - Line unwrapping algorithm: unwraps 1 line along X from center point, then unwraps each line along Y from center line
 - Uses 3 shifted-phase angle estimates and voting to separate wrapping events from real discontinuities
 - Consistency checking among multiple inner-loop estimates also used to identify unwrapping artifacts



WF Sensing Example



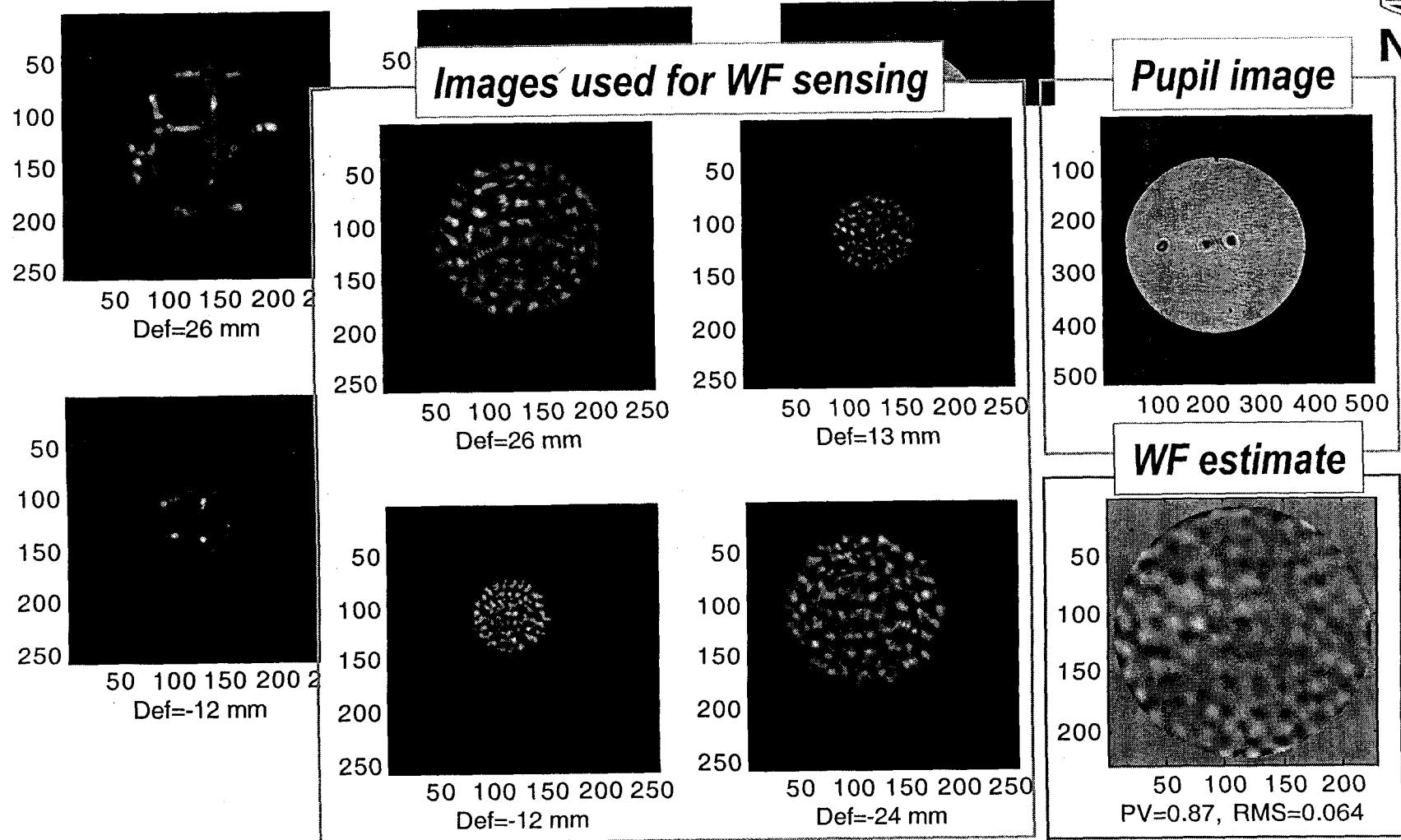
- Random aberration applied using telescope simulator DM
 - WFE = 1.6 waves peak-to-valley, 0.27 waves RMS



WF Control

- Controls are calibrated by "poking" actuators and segments, then measuring the WF
 - $WF_{poke} - WF$ = the effect of that actuator
 - Build up a sensitivity matrix recording the effect of *all* actuators on the WF
- Feedback form is determined by "inverting" the sensitivity matrix
 - Yields a gain matrix that transforms a WF into equivalent actuator commands
 - Control then applies the negative of these commands to null the WF
 - Constraints are imposed to protect the mirrors

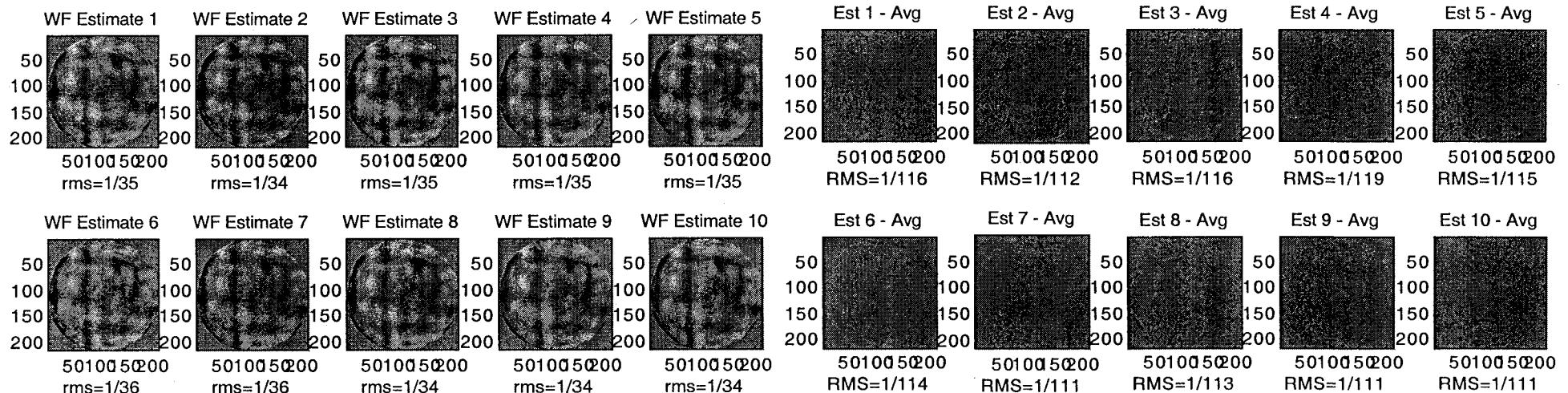
...Example Successfully Controlled



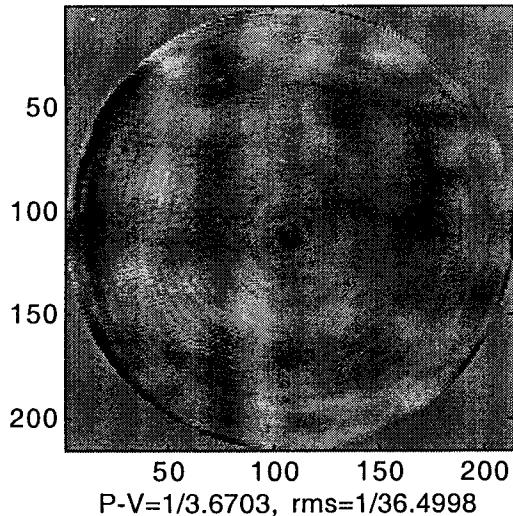
- Control reduces WF error
 - Initial WFE = 1.6 waves peak-to-valley, 0.27 waves RMS
 - After control WFE = 0.87 waves PV, 0.064 waves RMS



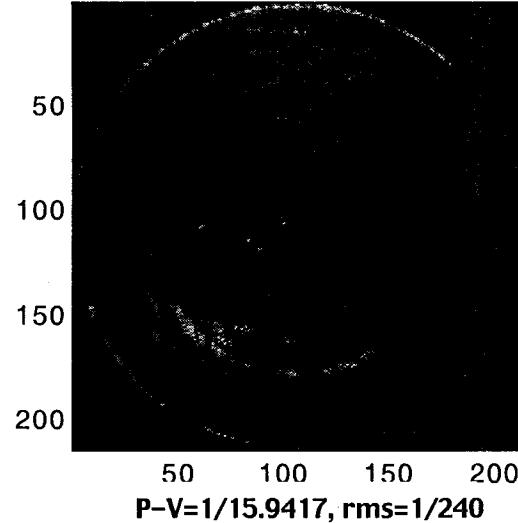
WFS Highly Repeatable



Mean WF Estimate



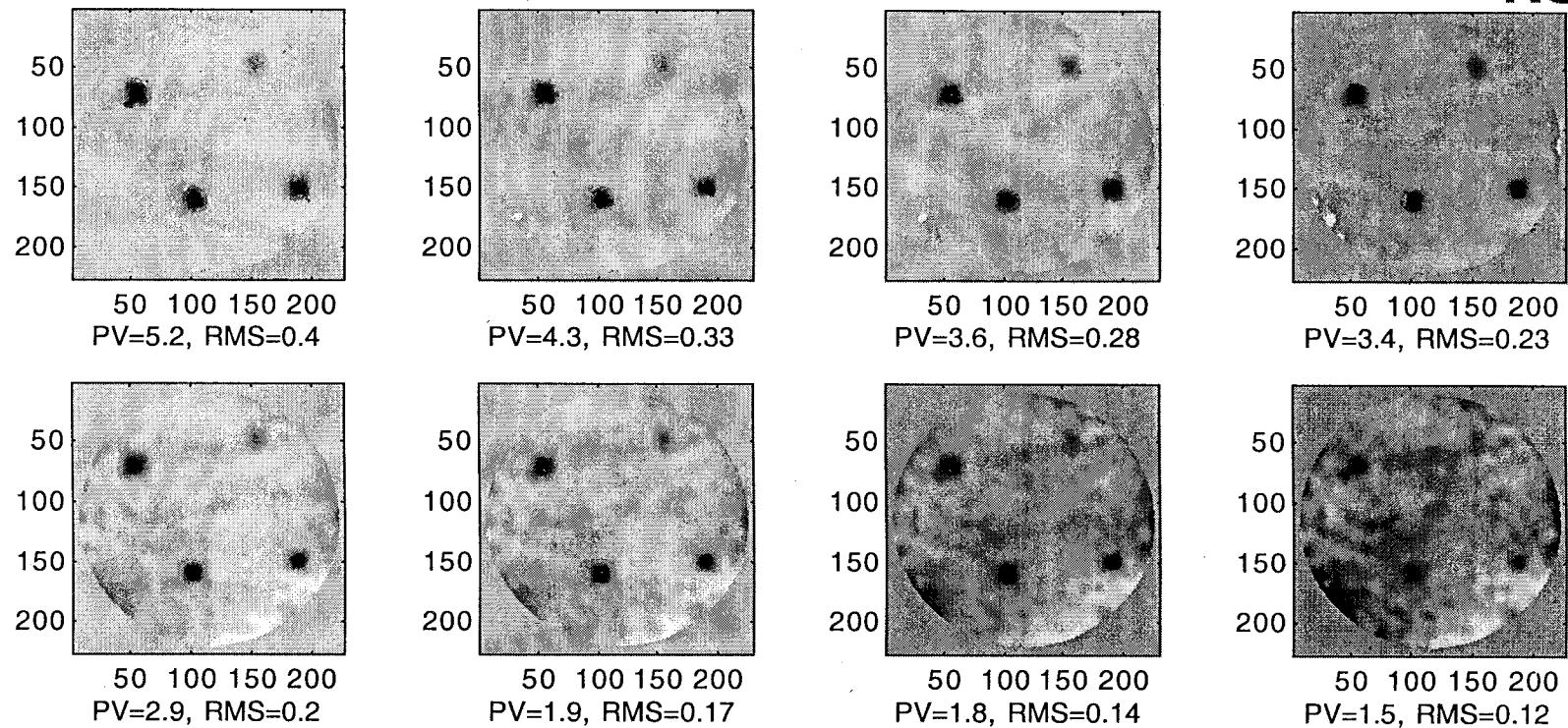
WF Estimate Std Dev



- WFS repeatability $< \lambda_{633}/110, < \lambda_{2000}/300$ for undersampled WCT

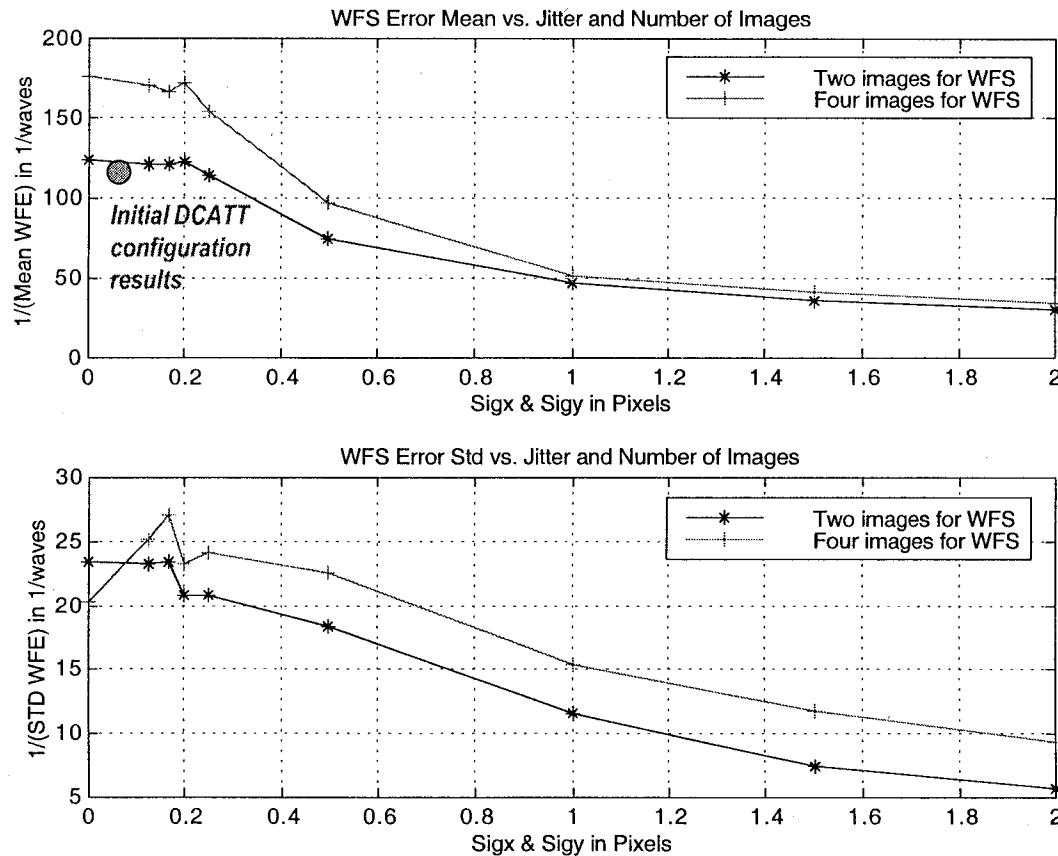


DM Pokes Show Good Dynamic Range



- DM actuator “poke” patterns provide a high spatial-frequency, high dynamic range test
- Pokes exceed 5 waves WF in this example

WFS Insensitive to Jitter



Monte Carlo simulation, 100 trials/pt

DCATT optics

Double-pass telescope

Random misalignment

WFE < 1 wave for each case

15 DN read noise

12 bits dynamic range

Phase retrieval parameters

$\lambda = 632.8 \text{ nm}$

2x oversampled

Two images:

Defocus = $\pm 15 \text{ mm}$

Four images:

Defocus = $\pm 15, \pm 7.5 \text{ mm}$

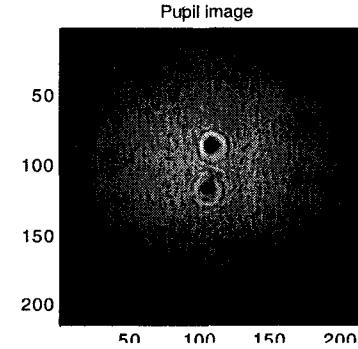
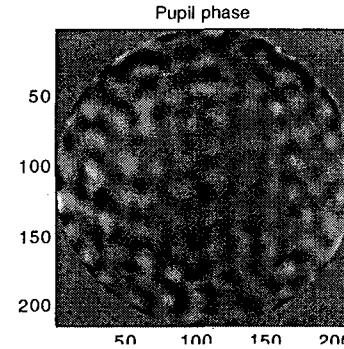
2 images run to full well

- Modeling results indicate good performance possible even with significant jitter
- Born out by results using current WCT configuration
 - Data at 0.1 pixel jitter
 - Reliable WFS in high jitter cases (0.4 pixel)

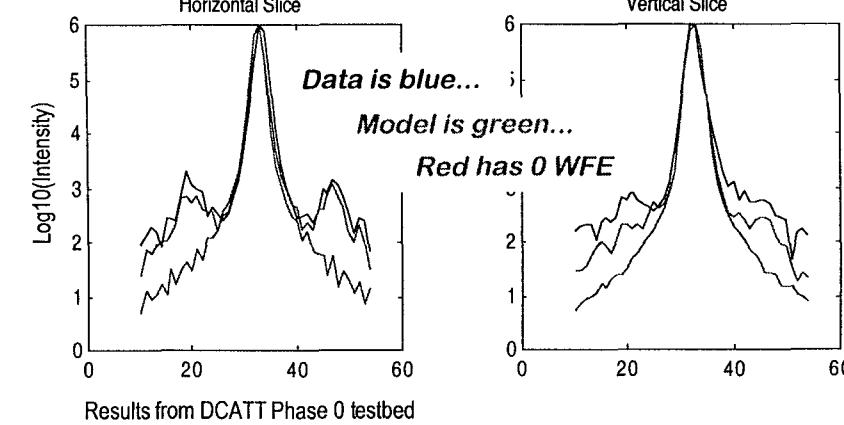
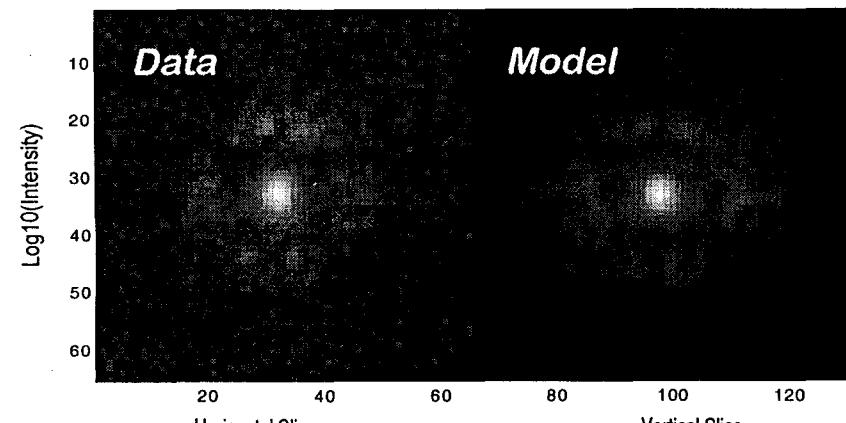
Deep In-Focus PSF at Vis and NIR



This measured pupil phase and intensity...

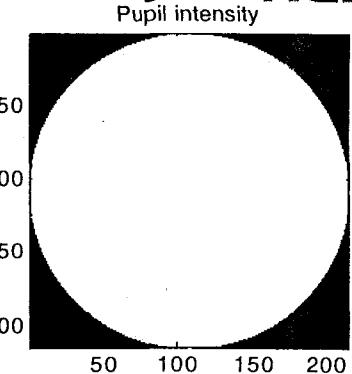
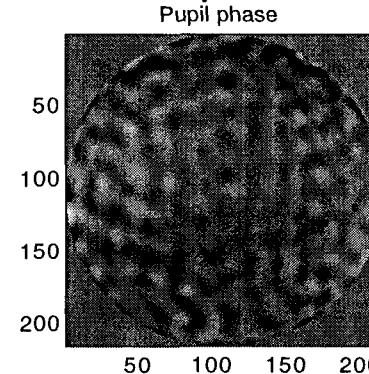


...produces these PSFs at $\lambda = 633 \text{ nm}$:

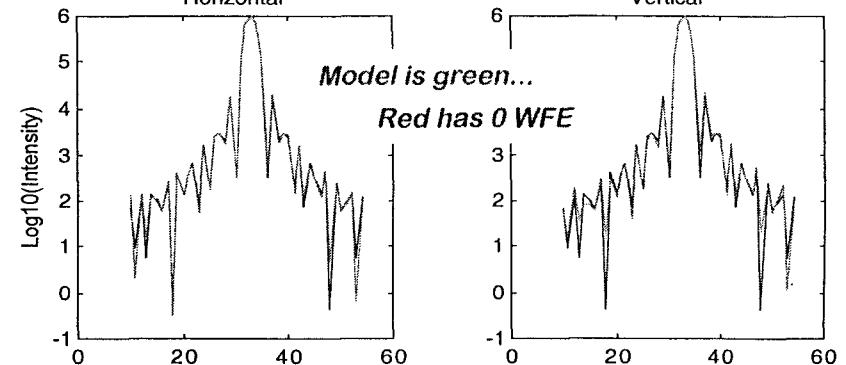
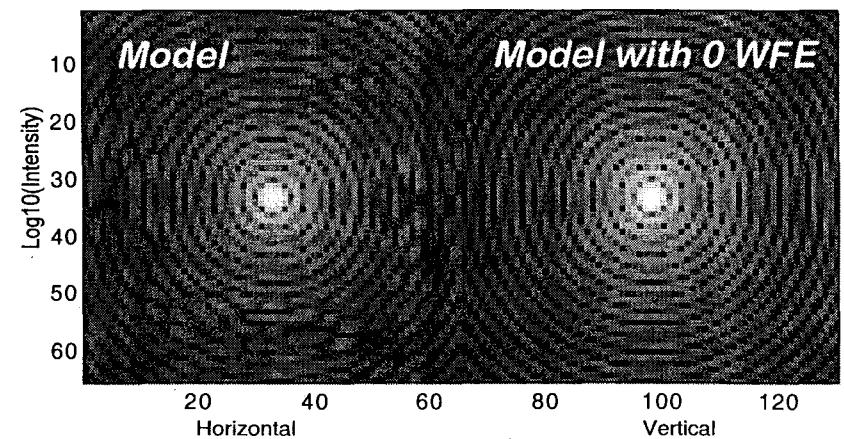


Results from DCATT Phase 0 testbed

The same phase with flat intensity...



...produces these PSFs at $\lambda = 2 \mu\text{m}$:



Conclusion



- All NGST WFS&C phases have been successfully demonstrated in sim and on the WCT hardware
- Performance exceeds NGST requirements